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AN EXPERIMENTAL MICROCOMPUTER CONTROLLED SYSTEM FOR SYNCHRONIZED PULSATING ANTI-GRAVITY SUIT *

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ABSTRACT

An experimental system to deliver synchronized external pressure pulsations to the lower body is described in this technical note. The system is designed using a microcomputer with a realtime interface and an electro-pneumatic subsystem capable of delivering pressure pulses to a modified anti-G suit at a fast rate. It is versatile, containing many options for synchronizing, phasing and sequencing of the pressure pulsations. Details of its software and hardware are described along with the results of initial testing in a Dynamic Flight Simulator on human volunteers.

Key words : Acceleration protection, G tolerance,
External counterpulsation

I. INTRODUCTION

This technical note describes a microcomputer-controlled system and a modified anti-G suit which provides synchronized external pressure pulsations (SEP) to the lower body. It was designed to study the efficacy of SEP in augmenting tolerance to acceleration stress.

The standard anti-G suit is capable of increasing tolerance to G_z acceleration by approximately 1 G [4]. This suit contains interconnected calf, thigh and abdominal bladders which can be inflated. The pressure in the bladders increases with increasing acceleration stress. The pressure applied by the suit to the lower limbs and the torso can prevent pooling of blood in the lower extremities and counteract the decrease in blood pressure in the central circulation resulting from the acceleration forces. In addition to the G suit, muscular straining maneuvers and positive pressure breathing [11] can also be used to augment G protection. The level of protection provided by these techniques, however, is insufficient under the maneuverable capabilities of today's high performance aircraft.

The cardiovascular benefits afforded by External Counterpulsations, a form of SEP, suggest that this method, or a variation of it may be useful for augmenting G tolerance. External Counterpulsation has been used in the clinical setting to aid the function of the cardiovascular system [2,8,14]. Cardiovascular function is augmented by providing a pressure perturbation in synchrony and out of phase with the cardiac cycle. When properly phased for clinical use, this form of SEP can result in increased cardiac output, diastolic arterial pressure, coronary flow and venous return, and in

decreased systolic arterial pressure and cardiac oxygen consumption. This technique has been used as a noninvasive treatment for cardiac failure and as early treatment of myocardial infarction and for support before and after cardiac surgery [1,12]. The hypothesis underlying our work is that pressure pulsations could be optimized to provide augmentation of cerebral blood flow and venous return, thereby reducing the two major deleterious effects of acceleration stress.

The concept of using SEP as a means of increasing G_z protection has previously been investigated [3,10]. The results from these studies were inconclusive, partly due to equipment limitations. Our earlier theoretical study, using a nonlinear computer model of the cardiovascular system, indicated that SEP might provide increased G protection. These predictions were later reinforced by results of human centrifuge experiments 9]. More recently, the idea has received further support from other laboratories, where an unsynchronized sequential pulsating suit is under development [13].

The new system described here was designed to study the feasibility of this concept and to provide the means by which the operational characteristics for increased acceleration tolerance can be determined. This system will be referred to as PAGS (pulsating anti-G suit). It permits a choice of different schemes of inflation/deflation sequences, and pressure levels of pulsation. The system requirements included :

1. synchronization of the pressure pulsations to a physiologic signal such as ECG or respiration,

2. control of the phasing of the pulsations in the cardiac cycle (systolic or diastolic) and/or the respiratory cycle (inspiratory or expiratory),

3. control of the high and low pressure limits during pulsation as a function of G level, so that the high pressure

$$P_H = P_{mean} + 0.5 \times P_{exc} \quad (1)$$

and the residual (low) pressure

$$P_L = P_{mean} - 0.5 \times P_{exc} \quad (2),$$

where P_{mean} is the mean pressure in the suit which is a function of G_z, and P_{exc} is the peak-to-peak excursion around the mean value.

4. individual control of timing and levels of pressurization (inflation and deflation) of the calf, thigh and abdominal bladders, and

5. capability of the pneumatic and electronic subsystems to withstand high acceleration levels.

A laboratory prototype of PAGS was designed to meet the aove requirements. The system was tested on human subjects in a Dynamic Flight Simulator (DFS) at the Naval Air Development Center (NADC), Warminster, PA.

II. SYSTEM DESCRIPTION

The PAGS system consists of three major functional subsystems. They are (i) a modified G suit, (ii) a pneumatic subsystem and (iii) a controller. The functional blocks of the PAGS are shown in Figure 1.

Modified G suit : Two standard Navy anti-G suits (CSU-15/P) are modified (by KEM-TEK, Linwood, PA) to provide five separate, nonconnected bladders: one for each calf, one for each thigh and one for the abdomen. The modifications include heat sealing the individual bladders and providing individual inlet/outlet ports.

Pneumatics : An air supply at 75 psi is used to feed a 6-gallon accumulator through a regulator. The accumulator pressure is set to 15 psi. The inflation of each bladder to its desired high pressure level is accomplished by opening the solenoid valve connecting the accumulator to the bladders. The valve is closed automatically when the desired bladder pressure is reached. This valve will be referred to, as the "inflate valve". Each bladder is deflated to its desired low pressure level (residual pressure) by venting it to atmosphere using another solenoid valve, which is closed automatically when the desired residual value is reached. This valve is called the "exhaust valve". A total of six general purpose, DC operated, two-way, normally closed, 1-inch orifice solenoid valves (type 8210D4, Automatic Switch Co, Florham Park, NJ) are used. The pair of calf bladders and the pair of thigh bladders are each pressurized by a single pair of inflate and exhaust valves. A third pair of valves

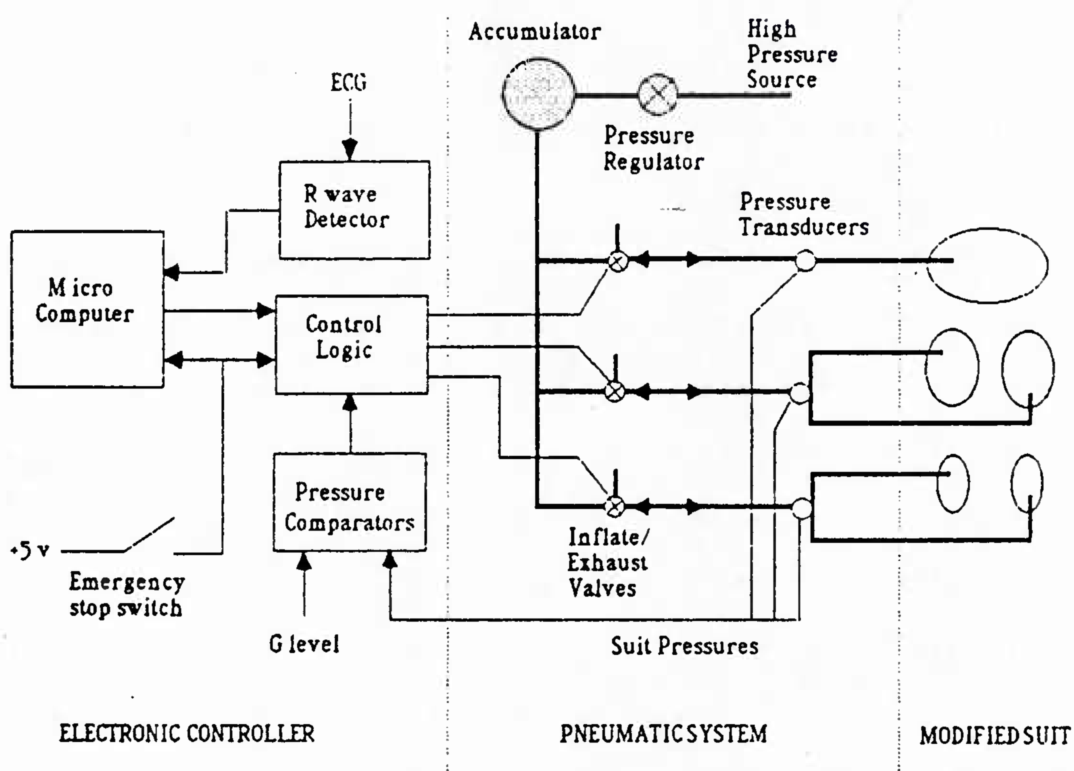


Figure 1:Functional block diagram of the synchronized pulsating anti-G suit (PAGS). The pneumatic connections are shown in bold lines.

controll pressure levels in the abdominal bladder. Pressure level in each of the bladders is monitored using pressure transducers.

Controller : A microcomputer subsystem controlls the timing, the duration, and the sequence of actuation of the solenoid valves through signals coupled to the valve drivers. The elecrocardiogram of the subject, the G level signal from the gondola of the DFS, and the outputs of the pressure transducers are used as inputs to the controller(Figure 1).

Upon detection of an R wave, a sequence of operations is initiated by the computer. These operations include computation of timings, based on the latest RR interval, for inflation, and deflation of all the valves and generation of INFLATE and DEFLATE signals. When the computer sends out an INFLATE signal, the valve control circuit energizes the appropriate valve drivers to initiate inflation of the suit bladders. Inflation is terminated when the pressure comparators indicate that the desired high pressure is reached. Similarly, deflation is initiated by the computer-generated DEFLATE signal and terminated by a signal from the pressure comparators.

A Franklin ACE1200 microcomputer is used for development and implementation of the software. It is an Apple II compatible, 8-bit, 6502-based machine. An interface chip, the versatile interface adaptor (VIA) 6522, is used for interfacing the computer to the R wave detector and the valve control circuit. Timers of the 6522 are utilized to generate the R wave-synchronized time intervals for starting inflation and deflation.

Software : The software consists of an interactive module for user input and a control module for real time computing and interfacing with external devices.

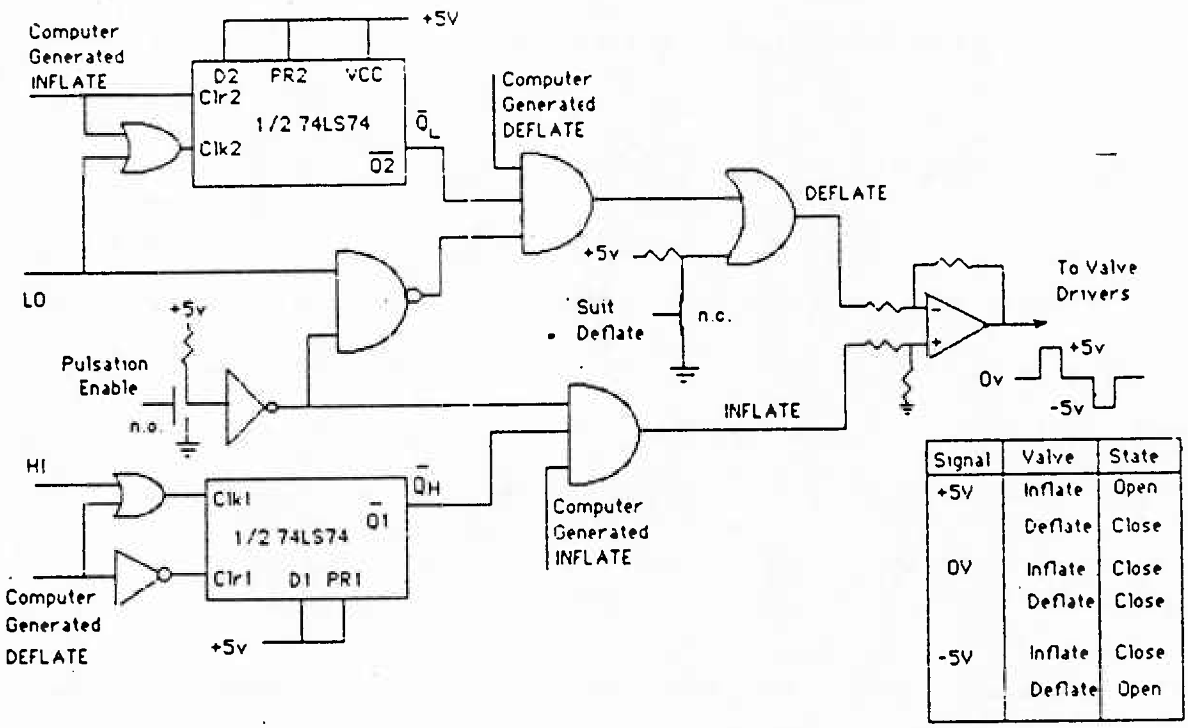
The interactive module, coded in BASIC, allows the user to specify a wide range of parameters for suit pressurization. These include the period of the cardiac cycle in which to inflate the suit (systolic or diastolic), the duration of inflation as a percentage of the R-R interval (duty cycle), the order of inflation of bladders (simultaneous or sequential), and the time delay between inflations of two adjacent bladders when the system functions in the sequential mode.

The control module, coded in 6502 assembly language, performs three real time computing tasks associated with the operation of the valves. It provids a clock base for measuring time intervals and scheduling various events. It monitors the incoming R wave and the system enable/disable signal, generates INFLATE and DEFLATE signals, and routes them to the valve logic circuit to open the appropriate valves.

Operation of the system proceeds in the following sequence. Detection of an R wave generates an interrupt to the processor. The time intervals between two consecutive R waves (R-R intervals) are stored in a table. The INFLATE and DEFLATE events (i.e., the time of opening of the inflate and the deflate valves), are scheduled on the basis of the latest R-R interval and the previously entered suit operational parameters. In the sequenced mode of operation, appropriate delays between inflation of the bladders are also generated.

The inflate valves open when the computer generates the INFLATE signal. Pressures in the bladders connected to those valves then starts to increase. These pressures are continuously compared with the desired high limit (P_H) as given by equation 1. The valves close when the pressure in the bladder reaches the desired level. Similarly, the deflate valves are opened by the DEFLATE signal of the computer. They close when the pressure in the bladders falls to the desired low pressure limit (P_L). Thus, the opening of both the inflate and deflate valves is controlled by the computer, while their closing is determined by the pressure transducer feedback provided through the pressure comparators.

Pressure Comparators and Valve Logic Circuit : To achieve independent control of pressures in the bladders, three sets of comparators, one each for the calf, thigh, and abdominal bladders, are used. Voltages corresponding to the upper and lower pressure limits are obtained from the incoming G signal and the desired pressure excursion. Outputs of the pressure transducers are compared with P_H and P_L using the two comparators. An output signal is generated by one of the comparators when the pressure in the bladder increases above P_H. The other comparator generates a similar signal when the pressure falls below P_L. These high (HI) and low limit indicator (LO) outputs, along with the computer-generated INFLATE and DEFLATE signals, drive the valve logic circuit (Figure 2) which provides the biphasic voltages to energize the appropriate valve drivers.



Signal	Valve	State
+5V	Inflate	Open
	Deflate	Close
0V	Inflate	Close
	Deflate	Close
-5V	Inflate	Close
	Deflate	Open

Figure 2:Circuit diagram of the valve control logic.

III. PRELIMINARY TESTS

The system was tested in two stages. In the first stage, experiments were conducted in a 1G environment to examine the functioning of the hardware and to assess the cardiovascular effects of pressure pulsations. Experiments were then conducted on the DFS at NADC to evaluate the performance of the pulsating suit under actual acceleration conditions.

1G Experiments : The pulsating suit was tested on 6 male student volunteers. Pressures in the suit bladders, ECG, Doppler velocity and the photoplethysmogram were monitored. Operation of the suit was studied under varying modes of timing, duty cycle, sequence of bladder inflation, and delay between inflations of adjacent bladders. The results of these experiments demonstrated the suitability of the hardware and software systems for pulsating the suit at the several intended modes of operation.

DFS Experiments : Seven US Navy volunteers were the subjects for these experiments. They were fitted with the pulsating suit, instrumented and seated in the gondola. The pneumatic subsystem, solenoid valves and drivers, and pressure transducer amplifiers were also located in the Gondola. The solenoid valves were mounted with their plungers perpendicular to the applied G_z force to minimze the effect of acceleration on their performance during the run. DFS runs consisted of rapid and gradual onset acceleration profiles. For each of these acceleration profiles, two schemes of pulsations were employed. In one, high pressure was applied during the systolic phase of the cardiac cycle, while the low pressure was maintained during diastole. In the other, the higher pressure was applied during diastole. Accordingly, these

runs are referred to as pulsating systolic or pulsating diastolic runs respectively. In addition, suit pulsations were delivered either simultaneously to all three bladders or sequentially starting with the calf bladders and advancing with a delay of 80 milliseconds between bladders. Thus, four modes of PAGS operation were examined : systolic simultaneous, systolic sequential, diastolic simultaneous and diastolic sequential. In all, more than 300 DFS runs with relaxed subjects protected by PAGS were conducted. Details of the DFS runs with PAGS, and comparison of the results of PAGS protection in relaxed subjects with standard anti-G suit and with no protection appear elsewhere [5,6].

IV. RESULTS AND DISCUSSION

The PAGS performed well under simulated acceleration conditions in the DFS. The subsystems of the PAGS mounted in the DFS gondola, though not flight-rated, worked satisfactorily under G_z stress. Synchronization of pressure pulses was maintained effectively even at a heart rate of 180 beats/min. Failure to detect the R wave occured in only two out of 300 pulsating runs. One run had to be terminated due to excessive noise in the ECG during the run.

Figure 3 is a typical plot showing the pulsating pressures in the suit bladders along with ECG, light bar tracking, G level, pulsatile doppler velocity and plethysmogram recorded during a rapid onset DFS run.

All the chosen modes of suit operation were successfully tested. The PAGS was able to produce the desired phasing with respect to the cardiac cycle (systolic or diastolic), the order of pulsations (simultaneous or

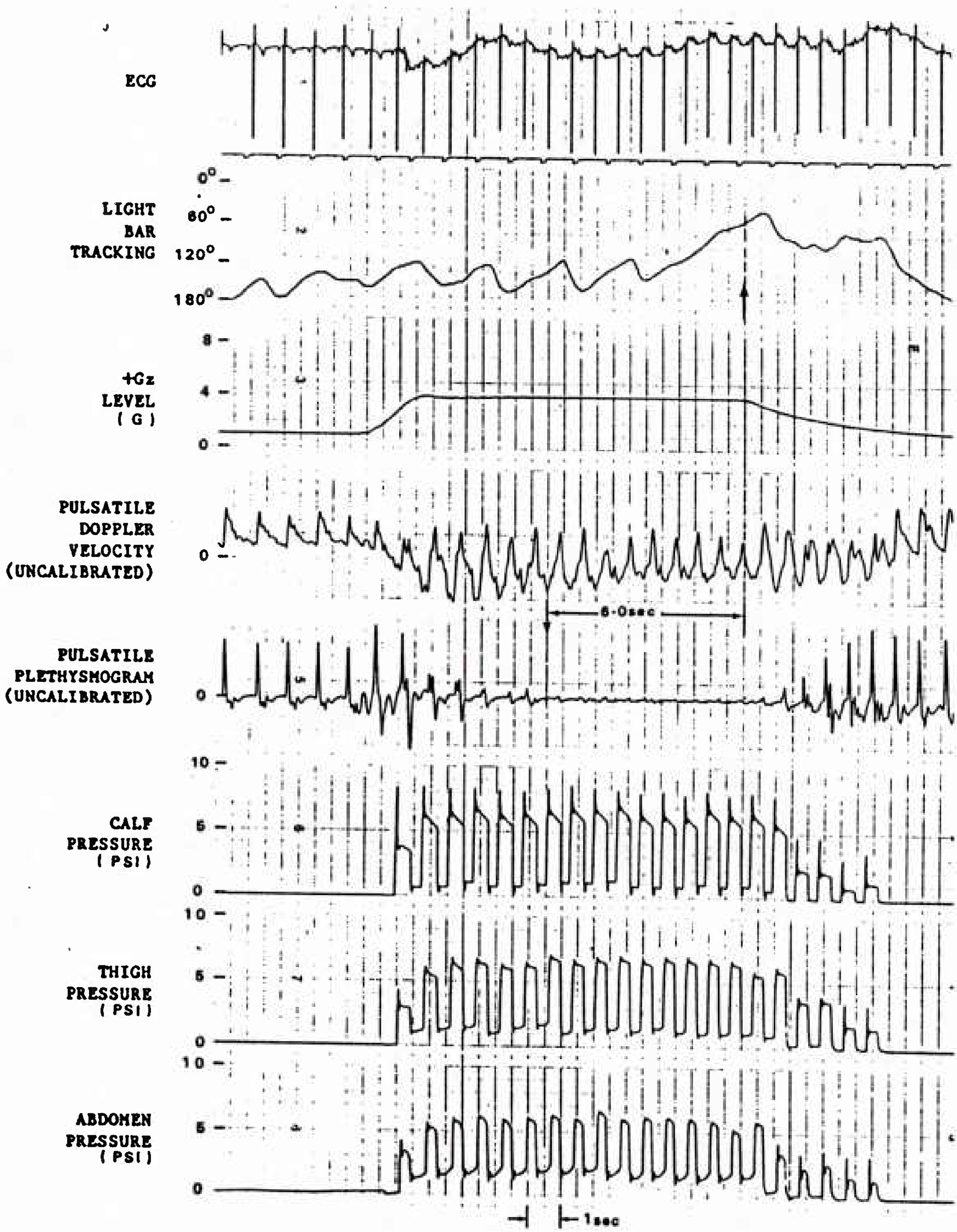


Figure 3:A sample plot of pulsating suit pressures along with ECG, light bar tracking, G level and Physiologic signals recorded during a rapid onset DFS run.

sequential) and the selected duty cycle. However, a few problems were encountered with the present system. On many occasions we could not maintain mean suit pressure in the suit. Two major factors accounted for this observation. 1. In the sequential mode, successive bladder inflation was delayed by 80 ms, while deflation was simultaneous. Because of the resulting 160 ms delay in inflation of the abdominal bladder, the duty cycle became markedly reduced at high heart rates. 2. The relationship between the mean pressure in the suit and the signal representing the G_z, maintained by varying the high and low pressure limits, was found to be nonlinear. As the combined result of both factors, the mean presure in the suit was substantially below the standard anti-G suit pressure. Difficulties were also experienced when the required, peak-to-peak pressure excursion was reduced below 3 psi. Electromechanical delay of the solenoid valves, nonlinearities in flow characteristics of the pneumatic system as well as unequal gains of the P_H and P_L limits contributed to these problems. A modified system which corrects the above problems is being prepared for new experiments.

The results of G tolerance testing with the PAGS indicated that of the various modes examined, the sequenced systolic pulsations provided the highest G protection. Even though the mean pressures in the suit were substantially lower than the standard anti-G suit pressure for corresponding G levels, the protection offered was comparable to that of the standard suit. In a previous study, it was found that G tolerance is directly related to the suit pressure [7]. Thus, it might be expected that with mean pressure similar to that in the standard ati-G suit, the pulsating suit would offer a higher level of protection against acceleration stress.

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